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DIVISION S-6—SOIL & WATER MANAGEMENT & CONSERVATION

Soil Wind Erosion Hazard of Spring Wheat–Fallow as Affected by Long-Term Climate and Tillage

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ABSTRACT

We hypothesized that drought accelerates wind erosion by increasing plant and soil factors of erodibility together, compounding the erosion hazard. Erodibility factors measured in biennial spring wheat–fallow on Pachic and Typic Haploborolls soil were (i) soil-inherent wind erodibility (SIWE) by rotary sieving, (ii) surface roughness by pin meter and chain methods, (iii) standing residue profile, and (iv) residue coverage photographically. Four tillage treatments ranged from low residue (LR) to no-till (NT). The erodible fraction of surface soil (a SIWE measure) changed from 53% during a dry period (1989–1990) to a less erodible 26% during a wet period (1992–1994). Median erosion protection values calculated from flat and standing residue measurements made after seeding were, respectively, 16 and 43% in 1989 to 1990, and 80 and 76% in 1992 to 1994. Soil losses estimated by RWEQ model equations were 11 to 6100 times greater during 1989 to 1990, compared with 1992 to 1994. No-till was protective, and estimated soil losses on LR were up to 3000 times greater than those on NT. However, low residue yields in 1988 (930 vs. 3640 kg/ha avg.) resulted in inadequate protection after seeding in 1990, even in NT; and soil losses in LR and NT were 13 and 8 Mg/ha, respectively. Results indicate biennial small grain–fallow is nonsustainable in the long term from a soil-erosion perspective.

Cropping systems that use fallow periods to store precipitation are a central feature of dryland agriculture in semiarid regions (Smika, 1983). The Great Plains region of the USA is subject to weather cycles, which include multi-year droughts approximately every 10 to 25 yr (Cannel and Dregne, 1983). Drought enhances wind erosion, and mechanical tillage greatly increases wind-erosion hazards of the widely used wheat–fallow system. In spring wheat–fallow, poor crop growth under drought reduces the amount of crop residue available for soil protection during the 21-mo fallow period.

To what extent can conservation tillage, either no-till or minimal till, reduce the vulnerability of wheat–fallow cropping to wind erosion? Adequate research to answer this question has not been available previously because two necessary elements were lacking: (i) quantitative measurements of both the crop residue and soil factors of wind erodibility in a wheat–fallow system over a multi-year wet–dry weather cycle, and (ii) application of a functional model containing modern observations of wind erosion in the field so that wind erosion hazards may be quantified.

Soil wind erodibility is the tendency of surface soil to resist or be vulnerable to being transported by wind.

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Abbreviations: ASD, aggregate size distribution; CC, fraction of canopy cover; COG, RWEQ combined residue–plant materials factor; C_{par}, soil chain roughness measured parallel to tillage orientation; C_{per}, soil chain roughness perpendicular to tillage orientation; CT, conventional-till; EF, erodible fraction; GMD, geometric mean diameter; H, ridge height; K, RWEQ soil roughness factor; K_r, ridge roughness factor; LR, low-residue (tillage); MT, minimal-till; NT, no-till; Q, transported soil; Q_{max}, wind transport capacity (maximum transported soil); R_c, rotational coefficient for roughness factor; RWEQ, revised wind erosion equation (model); s, RWEQ critical field length; S, average interval between ridges; SA, standing residue silhouette area per ground area; SC, percent residue cover; SCF, RWEQ soil crust factor; SIWE, soil-inherent wind erodibility; SLR, soil-loss ratio; SLR_C, RWEQ soil loss ratio for plant canopies; SLR_F, RWEQ soil loss ratio for flat residue; SLR_S, RWEQ soil loss ratio for standing residue; WF, RWEQ weather factor.

The ability of wind to cause erosion is strongly and nonlinearly dependent on wind energy and is termed *wind erosivity* (Lyles et al., 1983). Soil wind erodibility has both soil and plant components. The soil components include (i) soil-inherent wind erodibility (SIWE; Merrill et al., 1999); (ii) soil surface microtopography, often termed *soil roughness*; and (iii) soil wetness, which includes soil water content and snow coverage. SIWE is defined as the resultant of all properties of soil, excluding soil microtopography and soil wetness, that relate to its wind erodibility. The plant components of wind erodibility include (i) the areal coverage effect of plant residues, and (ii) the profile effect of standing plant residues and plants. Although we define components of wind erodibility for scientific discussion, in nature they interact and are difficult or impossible to separate. For example, aerodynamic roughness depends on both soil roughness and the profile of dead and live plant material. Soil aggregation, which dominates SIWE, affects soil roughness.

Although SIWE includes an array of surface soil properties, as reviewed by Zobeck (1991), it appears to be dominated by the combination of aggregate size distribution (ASD) and aggregate stability. Dry aggregate size distribution was related to wind erosion, according to Chepil (1950), who observed that soil aggregates <0.8-mm diam. were highly erodible. The principal instrument used to produce a measurement of dry ASD is the rotary sieve (Chepil, 1962). However, rotary sieves abrade aggregates and thus, for most soils, sieve measurements include some significant component of aggregate stability. This was acknowledged by Chepil (1952), who prescribed measurement of aggregate stability by multiple repassage of soil separates >0.84-mm diam. through the rotary sieve. The erodible fraction (EF) of soil (percentage of aggregates <0.84 mm, based on rotary sieve determination of dry ASD) is currently the principal functional measure of SIWE.

A variety of devices have been used to measure soil roughness, and a number of indices have been prescribed to summarize the data, as reviewed by Zobeck and Onstad (1987). In the past, pin meters have been the dominant devices used for roughness. Saleh (1993) has described roughness measurement by use of a roller chain, which is more convenient than using a pin meter. The validity of roughness measurement using a single roller chain has been discussed by Skidmore (1997) and Saleh (1997). Merrill (1998) has shown theoretically that using a set of chains with different linkage lengths will overcome any problems of invalid measurements due to possible scale insensitivity arising from the use of a single, finely linked chain.

The effect of soil roughness on wind erosion has been studied using wind tunnels (Fryrear, 1984; Hagen and Armbrust, 1992).

The plant residue and plant factors of wind erodibility are measured as percent surface coverage for flat residue and as area of profile per unit land area for standing residue (stubble) and plants. Bilbro and Fryrear (1994) have summarized wind tunnel research relating crop plant residue factors to wind-erosion potential.

Long-term studies of SIWE have been carried out in spring wheat–fallow systems using rotary-sieve measurements of ASD. Larney et al. (1994) studied effects of tillage on over-winter ASD changes during the fallow phase of spring wheat–fallow cropping for 5 yr. The study that most clearly demonstrated effects of a multi-year wet–dry weather cycle on the SIWE aspect of wind erodibility was conducted by Bisal and Ferguson (1968) in Saskatchewan on spring wheat–fallow. Their ASD measurements on three soil types over a 12-yr period showed that multi-year drought caused large increases in erodible fraction. Moulin and Townley-Smith (1993) used 14 years of ASD data from Saskatchewan spring wheat–fallow to show that year-to-year variations due to weather changes were greater than the effects of tillage or herbicide usage.

The wind-erosion hazards implied by measured soil wind erodibility values in a cropping system may be estimated by two current wind erosion models. Scientists of the USDA–ARS have developed a deterministic and process-oriented model known as the Wind Erosion Prediction System (WEPS: Hagen, 1991). USDA–ARS scientists have also developed another process-based but more empirical model using a factor multiplication approach that is known as the Revised Wind Erosion Equation (RWEQ: Fryrear et al., 1998). Both models had available for their development numerous wind-tunnel studies of erodibility factors and field measurements of wind erosion during storm events (Fryrear et al., 1991; Fryrear and Saleh, 1996; Fryrear et al., 1998).

We present here a report on the measurement of soil and crop residue factors of wind erodibility over a major portion of a significant Great Plains weather cycle. Measurements were made on a normally non-wind-erodible soil under a spring wheat–fallow rotation using a spectrum of modern tillage practices. The wind-erosion hazard has been estimated by using the RWEQ model.

MATERIALS AND METHODS

Experimental Cropping System

Wind-erodibility measurements were made in a spring wheat–fallow rotation that was part of a long-term conservation tillage experiment (Merrill et al., 1996; Black and Tanaka, 1997), located near Mandan, ND, and initiated in 1984. Soil at the site is classified as Temvik-Wilton silt loam (fine-silty, mixed Typic and Pachic Haploborolls).

Tillage was conducted during the fallow year and immediately before seeding during the crop year. Tillage treatments (Table 1) were managed to attain various levels of residue cover after seeding: (i) low-residue (LR) tillage—10% or less cover by disk and undercutter (sweeps); (ii) conventional-till (CT)—0 to 30% cover by tandem disk and undercutter; (iii) minimal-till (MT)—30 to 60% cover primarily by undercutter; and (iv) no-till (NT)—60% or greater cover. Herbicides were used in all treatments, but were used most often in MT and NT treatments.

The crop rotation consisted of four management periods:

1. From harvest in August until the next May, all tillage treatments were covered with crop plant stubble.
2. The next period was from May until the end of the year and is called the *first-year-fallow* period. Various types

Table 1. Seeding date, annual precipitation, and average crop residue (non-seed biomass) yield of crop phase year of biennial spring wheat–summer fallow cropping system, and sequence of cultural operations in subsequent fallow year for tillage treatments.

	Year seeded								
	1986	1987	1988	1989	1990	1991	1992	1993	1994
Date seeded	5/1	4/30	5/5	5/5	5/5	5/8	5/1, 5/14	5/4–5/5	5/9
Annual precipitation† (mm)	665	449	254	250	340	414	368	669	455
Residue yield‡ (kg/ha)	4160	3214	930	2440	3580	4930	4670	4360	4470
Year followed	1987	1988	1989	1990	1991	1992	1993	1994	
	Date of first fallowing tillage and subsequent cultural operations								
Low-residue till	4/22 B,§ 4/28 DD, S, S, U, S	4/27 DD, D, S, S	5/18 DD, U, S, S	5/17–19 DD, S, S	6/11 DD, D, U	5/4 DD, S, S, U	5/4 DD, D, D, S, D	5/6 DD, D, D, U	
Conventional till	5/14 U, U, U, S	5/23 D, U, S, S	5/28 D, U, S, S	5/17–19 D, S, S	5/30 U, U, S, U	5/20 U, S, S, U, S	S, 8/2 D	6/1 U, U, S, U	
Minimal till	5/14 U, S, S	5/23 U, S, S	518 U, S, S, S	5/17–19 U, S, S, S	5/30 U, S, S	5/20 U, S, S, S, S	S, S, 8/4 U	6/1 U, S, S, U	
No till	S, S, S	S, S, S	S, S, S	S, S, S, S	S, S, S	S, S, S	S, S	S, S	

† Long-term mean precipitation at locality is 410 mm.
‡ Aboveground non-seed biomass higher than 5 cm above soil surface.
§ Abbreviations: B, burned with fire; DD, deeper (offset) disking; D, shallower (tandem) disking; U, undercutter (sweeps); S, herbicidal spraying.

of tillages occurred, depending upon the treatment (Table 1).

3. The third period, called *second-year-fallow*, started at the beginning of the year and ended with various preplant tillages that occurred immediately before seeding in early May.
4. The *after-seeding* period began with seeding and ended with harvest in August.

Two series of plots existed—Series A, fallowed in even-numbered years, and Series B, fallowed in odd-numbered years. Besides tillage, there were two crop cultivar treatments and three N fertilization levels. The experimental design was strip-strip-split plot, with tillage and N-fertilization stripped, and cultivar as subplots. Cultivar and N-fertilization appeared to have relatively low effect on residue production and other wind-erodibility factors compared with the effects of tillage and climate variance. Thus, wind-erodibility measurements were taken without regard to crop cultivar or N-fertilization. There were three replications of treatments. The CT, MT, and NT treatments were randomized within one set of 73- by 137-m field blocks initiated in 1984. The LR treatment was carried out on another 73- by 34-m set of field blocks initiated in 1987 that were interspersed among the blocks carrying the other three tillage treatments. Field blocks were contained within a 22-ha area.

Wind-Erodibility Measurements

Surface soil was sampled about every 30 d when soil was unfrozen and not covered by snow. Two triple-composited samples were taken from each replicate tillage plot to a depth of ≈3 cm with a flat-bottomed shovel fitted with depth guides. After air drying at 30°C, ASD was determined by passing 1.1 kg of soil through a rotary sieve described by Chepil (1962). This sieve produces size fractions of <0.42 mm, 0.42 to 0.84 mm, 0.84 to 2 mm, 2 to 6 mm, 6 to 19.2 mm, and >19.2 mm. We have analyzed and displayed ASD data as EF and as geometric mean diameter (GMD), which assumes aggregate weight is distributed log-normally with size (Gardner, 1956). Geometric mean diameter has a nonlinear, inverse relationship to EF.

Soil surface roughness was measured in 1989 and 1990 with a pin meter (Zobeck and Potter, 1988), an instrument in which the heights of 40 pins in a 1-m wide rack were electronically logged at 20 positions in a 1-m^2 area. The 40-pin rows of readings were perpendicular to the north-south tillage direction. One set of pin meter readings was made in each replicate tillage plot on a given date. During the period of this study, pin meter readings were not made in 1988 nor in 1991 to 1992.

Starting in 1993, surface roughness was measured by the chain method (Saleh, 1993), using a 1-m roller chain with 0.95-cm links. Five parallel- and perpendicular-to-tillage pairs of chain readings were taken in each tillage plot, with nonburied surface residues gently removed before laying the chain. Soil roughness, C_r, measured by chain, is expressed as a percentage value in Eq. [1]:

$$C_r = (1 - L1/L2) \times 100 \qquad [1]$$

where $L1$ is the horizontal distance between the ends of the chain as it lies on the soil and $L2$ is the length of the chain itself (Saleh, 1993).

Pin meter measurements were converted to chain roughness values by analysis of simultaneous pin meter and chain measurements taken on plots of the LR, MT, and NT treatments. For each correlative set (used for pin-to-chain conversion) of pin meter readings, 12 parallel and perpendicular chain measurements were made in the same 1-m^2 area. Tortuosity index value was calculated for each row and each column of both experimental and correlative pin meter data sets by dividing the distance defined by the line through the ends of the pins by the horizontal span of the pin row or column. Tortuosity values for pin elevation columns were related to parallel-to-tillage chain readings and values for pin elevation rows to perpendicular-to-tillage readings by linear regression (with intercepts fixed at zero, $R^2 = 0.96$ for the parallel set, and $R^2 = 0.82$ for the perpendicular set).

Crop residue coverage was measured by evaluating 1-m^2 areas in downward-view photograph slides taken with a wide-angle lens. Three photographs were usually taken in each tillage plot, and the residue cover percentage was evaluated by scoring 50 points on each slide. Weed plants were counted as residue.

Standing residue profile was measured by horizontal-view photographs taken with a telephoto lens at a distance of 5 m from a backboard placed parallel to seeding direction. Usually three photograph slides per plot were taken, and each slide was evaluated at 500 points. Residue silhouette area per unit of ground area was calculated from a calibration of stem number, width, and height.

The RWEQ Model and Its Application to Wind-Erodibility Measurements

The RWEQ model (Fryrear et al., 1998) is an estimator of long-term soil loss due to wind erosion. Based on field observations of soil movement resulting from windstorms (Chepil, 1946; Fryrear et al., 1991; Fryrear and Saleh, 1996), soil movement is represented by a steady state equation that assumes the existence of a wind transport capacity. If properties are assumed to be uniform, then the amount of soil transported past a point x downwind of the edge of an erodible area may be expressed as shown in Eq. [2] (Fryrear and Saleh, 1996):

$$Q(\mathrm{x}) = Q_{\max}\,\{1 - \exp[-(\mathrm{x}/s)^2]\} \qquad [2]$$

where $Q_{\max}$ is the maximum amount of soil that can be transported downwind and s is *critical* field length at which the transported load is 63.2% of $Q_{\max}$. The current RWEQ model (Fryrear et al., 1998) has been extended to allow soil conditions to vary over the area of computation, but we have assumed uniform properties and have used Eq. [2] in our implementation of RWEQ.

Average soil loss (kg/m^2) for a field of length y is calculated as $E = Q(\mathrm{y})/\mathrm{y}$. The parameters $Q_{\max}$ and s are determined by equations (Eq. [3] and [4]) carrying wind-erosivity and wind-erodibility factors (Fryrear et al., 1998):

$$Q_{\max} = 109.8 \times (\mathrm{WF} \times \mathrm{EF} \times \mathrm{SCF} \times K \times \mathrm{COG}) \qquad [3]$$

$$s = 150.71 \times (\mathrm{WF} \times \mathrm{EF} \times \mathrm{SCF} \times K \times \mathrm{COG})^{-0.3711} \qquad [4]$$

where WF is the weather factor, EF is the erodible fraction, SCF is the soil crust factor, K is the soil roughness factor, and COG is the combined residue–plant materials factor. The weather factor carries both wind erosivity information and erodibility information about soil wetness. All the other factors carry wind-erodibility information.

The weather factor, WF, is the product of a wind-erosivity factor and two wind-erodibility factors, one for soil water content and the other for snow cover. Wind erosivity in the WF is a wind energy value derived from a statistical distribution of recorded wind speeds at a location (Skidmore and Tatarko, 1990; Fryrear et al., 1998). All of the wind-erodibility factors in RWEQ, with the exception of EF, are used in the form of a soil-loss ratio (SLR), which is the value of soil loss with the factor present divided by soil loss without the factor ($0 \leq \mathrm{SLR} \leq 1$). We used the RWEQ (Fryrear et al., 1998) to calculate WF for Bismarck, ND, which is <10 km from the field site. Equations specified in RWEQ (see below) were used with measured data to calculate the other wind-erodibility factors that appear in Eq. [3] and [4] for dry (1989–1990) and wet (1992–1994) periods (Table 5). Estimated soil losses were computed for 15-d or lesser periods (following RWEQ practice) for a flat field 400 m on a side with uniform soil properties.

Soil-inherent wind erodibility (SIWE) is represented in RWEQ by two factors: EF and SCF. EF is calculated from the ASD. EF is the percentage of aggregates <0.84 mm; but in RWEQ, it is used as a decimal fraction ($0 \leq \mathrm{EF} \leq 1$). The soil crust factor (SCF) is set to a value of 1 immediately after tillage. Once 12 mm or more precipitation had accumulated since tillage, SCF was calculated with an equation (Eq. [5]) largely based on research by Hagen et al. (1992):

$$\mathrm{SCF} = 1/[1 + 0.0066(\mathrm{Cl})^2 + 0.021(\mathrm{OM})^2] \qquad [5]$$

where Cl is percent clay and OM is percent organic matter. In our study, clay content was 25.9% and organic matter was 3.72%, so SCF was equal to either 1.0 or 0.17.

The RWEQ soil roughness factor, K, was calculated from chain roughness values in the following manner: (i) Oriented chain roughness values were determined as differences between perpendicular-to-tillage and parallel-to-tillage chain readings ($C_{\mathrm{per}} - C_{\mathrm{par}}$; Table 3). (ii) Ridge heights, H, were calculated by assuming that oriented roughness could be represented by triangular tillage ridges and that the chain value for oriented roughness represented the surface tortuosity of such ridges (distance along the surface perpendicular to the ridges), and by using the field observation that the average interval between ridges, S, was approximately 25 cm. (iii) Values of H were then used (Eq. [6]) to determine K_{r}, the ridge roughness factor as:

$$K_{\mathrm{r}} = 4(H^2/S) \qquad [6]$$

(iv) An equation given in Saleh (1994) (Eq. [7]) was used to calculate the rotational coefficient, R_{c}:

$$R_{\mathrm{c}} = 1 - 3.2 \times 10^{-4}(\mathrm{A}) - 3.49 \times 10^{-4}(\mathrm{A}^2) + 2.58 \times 10^{-6}(\mathrm{A}^3) \qquad [7]$$

where A, the angle between the study location prevailing wind direction and tillage direction was set at 45°. (v) Values K_{r}, R_{c}, and measured values of C_{par} (Table 3) were applied (Eq. [8]) to the principal RWEQ equation for the soil roughness factor (Fryrear et al., 1998):

$$K = \exp[1.86(K_{\mathrm{r}} \cdot R_{\mathrm{c}}) - 2.411(K_{\mathrm{r}} \cdot R_{\mathrm{c}})^{0.934} - 0.124C_{\mathrm{par}}] \qquad [8]$$

The RWEQ combined residue–plant materials factor, COG, is the product of factors for flat residue ($\mathrm{SLR_F}$), standing residue ($\mathrm{SLR_S}$), and crop plants ($\mathrm{SLR_C}$). The equation for flat residue (Eq. [9]) depends on percent cover, SC:

$$SLR_{\mathrm{F}} = \exp(-0.0438 \cdot \mathrm{SC}) \qquad [9]$$

The equation for standing residue (Eq. [10]) depends on the silhouette area of residue per unit of ground area (SA in cm^2/m^2):

$$SLR_{\mathrm{S}} = \exp(-0.0344 \cdot \mathrm{SA}^{0.6413}) \qquad [10]$$

Both residue equations are from Bilbro and Fryrear (1994).

The crop factor is found in Eq. [11] as

$$SLR_{\mathrm{C}} = \exp[-5.614 \cdot (\mathrm{CC})^{0.7366}] \qquad [11]$$

where CC is the fraction of soil covered by crop canopy, which was calculated according to an equation (Eq. [12]) for spring wheat canopy cover (Fryrear et al., 1998):

$$\mathrm{CC} = \exp[-0.508 - 2577.09/(\mathrm{DAP})^2] \qquad [12]$$

where DAP is days after planting.

RESULTS AND DISCUSSION

Soil-Inherent Wind Erodibility (SIWE) Measurements

The time-courses of SIWE-relevant rotary-sieve measurements throughout a 7-yr period are displayed in Fig. 1A and 1B as geometric mean diameters (GMD) from aggregate size distribution (ASD) measurements. Low GMD values of about 1 to 2 mm in 1989 and 1990 indicated dusty, erodible soil surface conditions, and

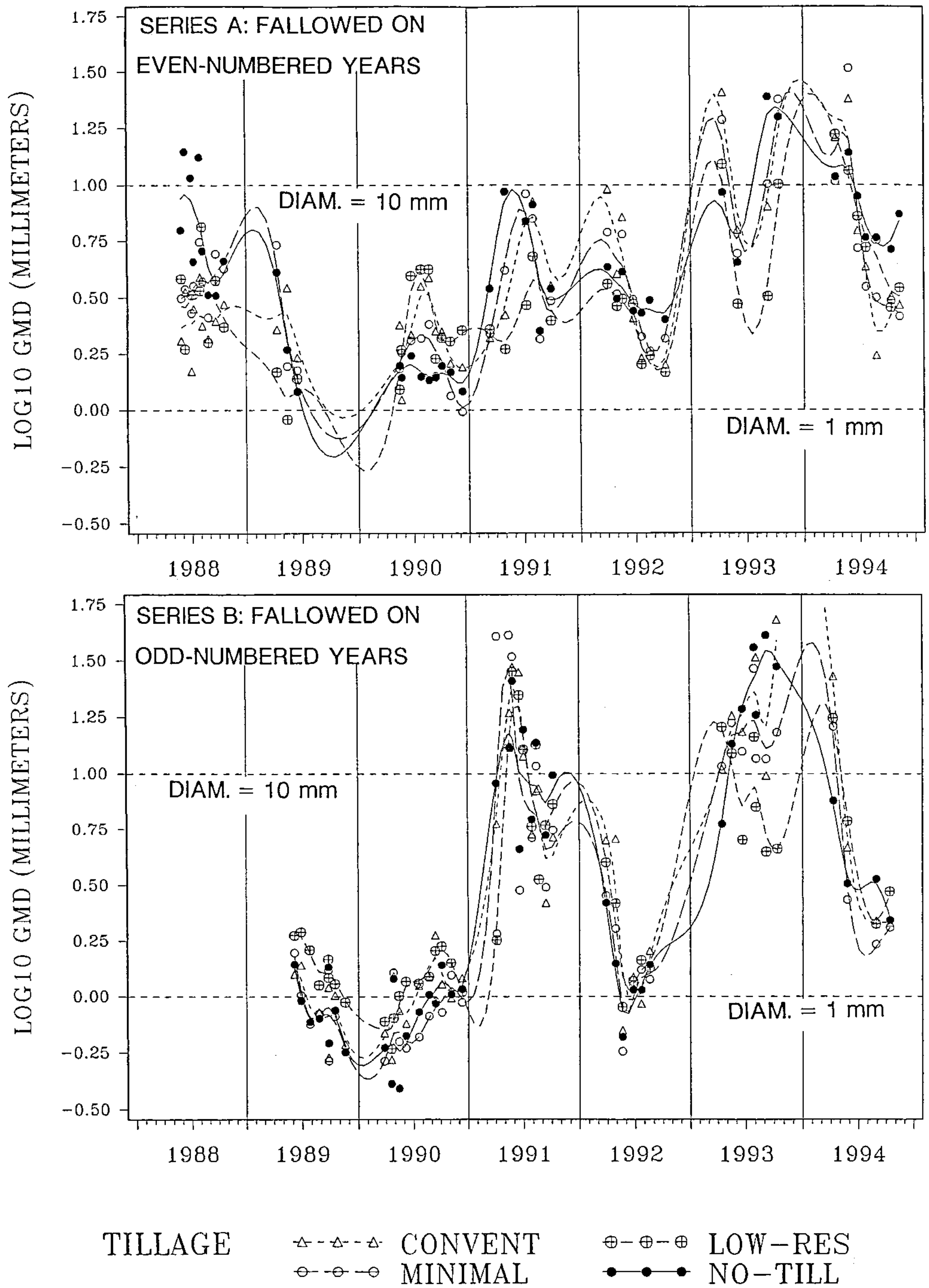

Fig. 1. Geometric mean diameter (GMD) of aggregate size distributions in logarithmic scale vs. time for tillage treatments. Series A: measured in plots fallowed on even-numbered years. Series B: measured in plots fallowed on odd-numbered years.

were associated with 250 and 254 mm precipitation in 1988 and 1989, respectively (Table 1), compared with a long-term average of 410 mm. GMD values of 5 to 10 mm or greater measured after 1991 indicated more cohesive soil conditions. The apparently greater variations in Series B plots (fallowed in odd-numbered years) compared with Series A (even-year fallowed) is probably due to the Series B plots being in stubble condition over the winter in 1990 to 1991 and 1992 to 1993. Aggregate rebuilding processes are typically stronger when the surface is covered with stubble, compared with tilled fallow conditions (Merrill et al., 1995).

The effects of tillage treatments on SIWE is indicated by compiling ASD measurements shown as average annual GMD and EF values in Table 2. Analysis of variance of the complete ASD dataset for both GMD and EF parameters revealed that crop rotation series (A vs. B), the interaction of year with crop rotation series, and date of sampling within year were all very significant sources of variation. Tillage treatment was not signifi-

Table 2. Measurements of aggregate size distributions presented as annual average geometric mean diameters and erodible fractions.

Calendar year	Year fallowed	Phase, crop or fallow	Number dates measured	Geometric mean diameter					Erodible fraction				
				LR‡	CT‡	MT‡	NT‡	Avg.	LR	CT	MT	NT	Avg.
				mm					%				
1988	1988	fallow	9	3.5b‡	2.8b	4.5b	9.6a	5.1	32.5a	33.4a	27.8b	23.2c	29.1
1989	1988	crop	3	1.3b	5.3a	3.0ab	2.7ab	3.1	47.2a	39.2b	39.2b	41.7ab	41.9
1989	1989	fallow	8	1.5a	1.0b	0.9b	0.9b	1.1	44.5b	51.3a	51.8a	51.8a	49.8
1990	1989	crop	11	1.1a	1.1a	0.8b	0.9b	1.0	48.9c	50.7b	54.5a	54.5a	52.1
1990	1990	fallow	9	2.9a	2.4a	1.8b	1.6b	2.2	36.3d	38.1c	41.5b	44.5a	40.1
1991	1990	crop	6	3.2b	6.2ab	6.0ab	9.9a	6.3	34.8a	29.4b	31.5b	31.5b	31.8
1991	1991	fallow	11	22.8a	26.7a	24.8a	24.6a	24.7	23.0b	24.9ab	27.0a	24.6ab	24.8
1992	1991	crop	6	2.2ab	3.0a	1.6b	1.5b	2.1	43.3b	43.5b	46.7a	43.3b	45.0
1992	1992	fallow	7	2.6b	5.6a	4.3ab	3.4ab	4.0	35.3a	32.0b	32.3b	31.3b	32.7
1993	1992	crop	4	8.5b	21.8a	21.9a	15.8ab	17.0	28.2a	19.3b	20.7b	19.0b	21.8
1993	1993	fallow	7	10.1c	31.7a	19.5b	28.5ab	22.5	20.2a	15.9b	19.0a	16.1b	18.0
1994	1993	crop	6	6.8ab	19.9a	5.0b	5.8ab	6.9	28.5b	30.2b	34.3a	29.6b	30.7
1994	1994	fallow	7	10.8a	11.9a	11.5a	10.1a	11.1	21.3b	24.3a	23.9a	18.3c	21.9

† Tillage treatments are: LR, low-residue; CT, conventional-till; MT, minimal-till; NT, no-till.
‡ Values in a row of four followed by the same letter are not significantly different at the 0.05 level by LSD test.

cant, and tillage treatments did not appear to have had consistent effects on ASD parameters. However, all of the annual sets of measurements except for two cases show at least one significant difference between means (Table 2). For 11 out of 13 rotation series by year averages, the greatest GMD values were found in either the LR or the CT treatments. EF averages were less consistent.

The highest average annual EF value found on our silt loam soil was 46.1% in 1990, slightly greater than 45.9% found in 1989 (Table 2). The lowest annual EF value was 19.9% in 1993, a drop of 57%. Bisal and Fergurson (1968) studied SIWE by rotary sieve in three Saskatchewan soils over a multi-year drought cycle in the late 1950s to early 1960s. Their measurements of EF in spring wheat–fallow rotations on sandy loam, loam, and clay soils showed decreases of 35, 48, and 79%, respectively, from highest to lowest annual averages.

Soil Surface Roughness

Roughness measurements made by pin meter in 1989 to 1990 and by chain in 1993 to 1994 are shown in Table 3. Pin meter measurements have been converted to chain roughness values. Measurements made perpendicular to tillage and seeding direction (C_{per}) represent the combination of oriented (ridge) and random roughness, while parallel measurements (C_{par}) indicate random roughness alone. Thus, C_{per} values were greater than or equal to C_{par} values in 41 out of 43 pairs of values in Table 3.

Roughness values for LR, CT, and MT treatments were greater than values for the NT treatment, as would be expected. Tillage was generally not deeper than 5 to 10 cm, and this is reflected in moderate to low roughness values. The highest roughness values in 1989 to 1990 were measured in May 1989, and primarily reflected effects of seed drill disturbance. Roughness values were higher in 1993 to 1994, and measurements made after seeding were similar in value, compared with those made in the first-year-fallow period.

The K-factor values (Table 3) calculated according to RWEQ model practice indicate the degree of protection against erosion attributable to soil roughness ($K = 1.0$ means no protection). K-factor values ranged from 0.87 to 0.16 in 1989 to 1990, and from 0.40 to 0.10 in 1993 to 1994.

The higher roughness values measured in 1993 to 1994 compared with 1989 to 1990 appear to be due to the fact that (i) less tillage was performed in 1989 to 1990 because of drier conditions (Table 1), and tillage caused less clod formation because of observably lower aggregate stability; and (ii) residue amounts were greater in 1993 to 1994, and the incomplete removal of flat residues before chain measurements could have inflated their values. The accuracy of converting pin meter readings to chain roughness is indicated by the fact that roughness values measured by pin meter in the after-seeding period in May 1989 were approximately comparable to chain measurements made during after-seeding periods in 1993 to 1994. Flat residue levels were lowest in the after-seeding period (Table 4), and chain readings should have been least affected by residue then.

Residue Factors of Wind Erodibility

Table 4 contains residue data in rows for plots fallowed in a given year, and displays data in columns for a given crop-management period.

Reduced crop plant growth in 1988, with average residue yields at harvest of 930 kg/ha (Table 1), resulted in reduced residue protection in NT and MT plots fallowed in 1989. Residue cover percentages in 1989-fallowed plots were 60 and 40% in NT plots during first-year-fallow and second-year-fallow periods, respectively, compared with average values of 84% in 1988 and 83% in 1991 to 1993. However, in plots fallowed in 1990, flat and standing residue values were not greatly different from overall averages, even though they were based on average residue yields of 2440 kg/ha at harvest in 1989. This was considerably lower than residue yields in 1987 and 1991 to 1994, which were all >4100 kg/ha.

Soil-loss ratio (SLR) values calculated from residue measurements (Table 4) show that standing residue was generally more protective (lower SLR values) than flat residue during the first-year-fallow management period. However, during the second-year-fallow period, stand-

Table 3. Soil surface roughness measured in tillage treatments by pin meter or chain methods.

Year in which fallowed	Crop/ fallow phase	N-times, dates (MMDDYY)	Pin meter or chain	Low residue till			Conventional till			Minimal till			No till		
				C_{par}†	C_{per}‡	K§	C_{par}	C_{per}	K	C_{par}	C_{per}	K	C_{par}	C_{per}	K
1988	2nd year fallow	1, 050389	pin	2.4a¶	2.8w	0.673	1.0a	1.6w	0.771	2.6a	2.5w	0.724	2.1a	2.8w	0.661
1988	after seeding	1, 051089	pin	7.2a	12.5w	0.196	8.6a	14.0w	0.164	8.5a	12.8w	0.186	6.9a	11.5w	0.220
1989	1st year fallow	5, 062689–101789	pin	3.0a	4.2w	0.587	2.5a	3.2x	0.629	1.5b	2.3xy	0.701	1.1b	1.4y	0.807
1989	2nd year fallow	2, 033090–042490	pin	3.3a	2.8w	0.664	1.2b	1.7x	0.766	1.0b	1.4x	0.801	0.7b	0.9y	0.867
1989	after seeding	1, 050890	pin	3.6ab	6.8wx	0.289	6.2a	8.0w	0.335	3.4ab	7.3w	0.366	2.0b	5.1w	0.478
1990	1st year fallow	3, 060490–092190	pin	2.8a	2.8w	0.707	2.5a	2.8w	0.679	4.5a	4.1w	0.572	2.6a	2.8w	0.685
Median values			pin	3.2	3.5	0.63	2.5	3.0	0.65	3.0	3.3	0.64	2.1	2.8	0.67
1992	after seeding	1, 051193	chain	5.6c	14.1w	0.158	8.2a	15.5w	0.125	7.6ab	15.0w	0.134	5.9bc	15.0w	0.153
1993	1st year fallow	3, 080493–102093	chain	6.5b	8.6y	0.226	9.8a	15.1w	0.115	9.7a	13.9x	0.125	3.0c	4.1z	0.401
1993	2nd year fallow	1, 050594	chain	3.1b	5.1x	0.347	9.2a	11.2w	0.163	8.3a	9.5w	0.204	2.5b	2.8x	0.524
1993	after seeding	1, 052594	chain	10.4a	17.7w	0.096	9.3ab	16.2wx	0.112	7.5b	14.6x	0.138	7.4b	10.5y	0.183
1994	1st year fallow	3, 062894–090994	chain	12.5a	15.3wx	0.100	11.8a	16.1w	0.096	9.5b	14.1x	0.125	4.6c	5.6y	0.334
Median values			chain	6.5	14.1	0.16	9.3	15.5	0.12	8.3	14.1	0.13	4.6	5.6	0.33

† C_{par}, soil surface roughness measured parallel to rows given as chain roughness value (percent: 0 = flat) or equivalent value for pin meter data.
‡ C_{per}, soil surface roughness measured perpendicular to rows given as chain roughness value (percent: 0 = flat) or equivalent value for pin meter data.
§ K, wind erodibility K-factor as a soil loss ratio (SLR, 1.00 = no protection), calculated by the RWEQ model.
¶ Values in a row followed by the same letter are not significantly different at the 0.05 level by LSD test.

ing residue SLR values were less protective than flat residue values. This reflects over-winter decay and flattening of standing residues (Steiner et al., 1994). For the NT and MT treatments, standing residue was more protective than flat, or the same, during the first-year-fallow period in 12 out of 14 cases; but flat residue was more protective, or the same as standing in 7 out of 8 cases during the second-year-fallow period. For the LR and CT treatments, standing residue was more protective than flat, or the same, during first-year-fallow in 9 out of 14 cases, but flat residue was more protective than standing during second-year-fallow in 6 out of 8 cases. This indicates that over-winter attenuation of the erosion protective effect is greater for standing residue than for flat.

Further disappearance, decay, and flattening of standing and flat residues occurred in the after-seeding management period, leading to increases in SLR values (Table 4). In the spring of 1990, standing residue SLR values in the NT and MT treatments increased to a significantly lower level of protection (SLR = 0.35 for both treatments). This compares with measurements made after seeding in 1993, which had considerably more protective standing residue SLR values of 0.09 and 0.19 for NT and MT treatments, respectively.

Application of the RWEQ Model

Wind-erosion hazards were quantified by soil losses calculated by applying the RWEQ model equations to measurements (Table 5). Soil losses are summed for crop-management periods. Estimated losses in the drought period 1989 to 1990 were from 11 to 6100 times greater than those estimated to occur in the wetter 1992 to 1994 period.

The much larger soil losses calculated under drought are the result of both soil and residue wind-erodibility factors being higher. The EF as a fraction averaged 0.53 under drought and 0.26 in the wetter period. Soil roughness K-factor for first- and second-year-fallow periods in 1989 to 1990 averaged 0.62, compared with 0.26 for 1992–1994. K-factor values for the after-seeding period, under droughted vs. wetter conditions, were 0.37 vs. 0.14. Crop residue factor values were more protective than roughness K-factor values in first- and second-year-fallow periods, and the products of flat- and standing-residue SLRs ($SLR_F \times SLR_S$) ranged from 0.34 to <0.01 in 1989 to 1990 and from 0.06 to <0.01 in 1992 to 1994.

The aggregate size distribution (ASD) aspect of SIWE is represented in RWEQ by erodible fraction (EF). The dependence of erosion on EF is assumed to be linear, and as previously noted, EF is used as a decimal fraction in RWEQ. The EF is an indicator of loose erodible material that wind turbulence above the threshold level moves so that the soil surface is abraded during a windstorm (Chepil, 1946; Hagen et al., 1992). Abrasion near the upwind boundary of a field generates more abrader particles, producing intermittent cascades of saltating particles near the soil surface (Stout and Zobeck, 1996).

Because of the nature of the wind-erosion process, and because EF determined by rotary sieve represents aggregate stability as well as a strictly *natural* ASD, the dependence of soil loss on EF is probably generally nonlinear. According to the earlier Wind Erosion Equation (WEQ) model (Woodruff and Siddoway, 1965), soil loss is nonlinearly dependent on EF to a power greater than two. Thus, potential soil loss during the drought period in our study may have been relatively higher than the 53 vs. 26% difference in measured EF would indicate.

Residues conserved with no-till ordinarily protect soil from wind erosion, and calculated soil losses for the NT treatment were 230 to 3000 times lower than losses for

Table 4. Percentage of surface residue cover (SC) and standing residue silhouette area (SA) for tillage treatments for three of four management periods in spring wheat–fallow rotation. Also shown are Soil Loss Ratios (1.00 = no erosive protection) for surface residues (SLR_F) and standing residues (SLR_S), which were calculated according to equations (Bilbro and Fryrear, 1994) used in the Revised Wind Erosion Equation (RWEQ) model.

	1st-year fallow (May–Dec.)				2nd-year fallow (Jan.–May)				After seeding (May–Aug.)			
	Surface		Standing		Surface		Standing		Surface		Standing	
	SC	SLR_f	SA	SLR_S	SC	SLR_f	SA	SLR_S	SC	SLR_f	SA	SLR_S
	%		cm²/m²		%		cm²/m²		%		cm²/m²	
Year fallowed			1988				1988					
Low-reisidue	21	0.40	50	0.65	13	0.56	50	0.65				
Conventional	44	0.14	270	0.28	34	0.23	100	0.51				
Minimal-till	61	0.07	1500	0.02	65	0.06	950	0.06				
No-till	78	0.03	2430	0.01	82	0.03	2020	0.01				
No. dates; months/year	4; Jun.–Nov./88		4; Aug.–Oct./88		1; Apr./89		1; Apr./89					
Year fallowed			1989				1989				1989	
Low-reisidue	9	0.67	100	0.51	8	0.70	90	0.53	4	0.84	20	0.79
Conventional	37	0.20	460	0.17	58	0.08	170	0.39	2	0.94	20	0.79
Minimal-till	45	0.14	500	0.15	27	0.30	240	0.31	4	0.84	200	0.35
No-till	60	0.07	1310	0.03	40	0.17	290	0.26	12	0.60	200	0.35
No. dates; months/year	4; Jun.–Oct./89		3; Jun.–Aug./89		1; May/90		1; May/90		1; May/90		1; May/90	
Year fallowed			1990				1990					
Low-reisidue	22	0.39	170	0.39	15	0.53						
Conventional	40	0.17	440	0.18	38	0.19						
Minimal-till	70	0.05	1560	0.02	67	0.05						
No-till	79	0.03	2140	0.01	87	0.02						
No. dates; months/year	6; May–Nov./90		4; Jun.–Oct./90		1; Apr./91							
Year fallowed			1991				1991					
Low-reisidue	20	0.42	140	0.43	21	0.40	180	0.38				
Conventional	47	0.13	1010	0.05	45	0.14	140	0.43				
Minimal-till	60	0.07	1520	0.02	52	0.10	690	0.10				
No-till	83	0.03	1960	0.01	72	0.04	440	0.18				
No. dates; months/year	3; Jul.-Sep./91		2; Jul.–Sep./91		1; Apr./92		1; Apr./92					
Year fallowed			1992				1992				1992	
Low-reisidue	17	0.48	520	0.14	27	0.31			11	0.62	370	0.21
Conventional	54	0.10	1540	0.02	65	0.06			34	0.22	510	0.15
Minimal-till	66	0.06	1900	0.01	72	0.04			35	0.21	410	0.19
No-till	84	0.03	2330	0.01	86	0.02			73	0.04	750	0.09
No. dates; months/year	3; Aug.–Oct./92		4; Jun.–Oct./92		1; Apr./93				1; May/93		1; May/93	
Year fallowed			1993				1993				1993	
Low-reisidue	25	0.33	470	0.16	36	0.21	10	0.86	12	0.60		
Conventional	62	0.07	1170	0.04	74	0.04	60	0.62	40	0.18		
Minimal-till	70	0.05	1540	0.02	71	0.05	290	0.26	39	0.18		
No-till	90	0.02	1920	0.01	91	0.02	510	0.15	70	0.05		
No. dates; months/year	4; Jun.–Oct./93		4; Jun.–Oct./93		1; Apr./94		1; May/94		1; May/94			
Year fallowed			1994									
Low-reisidue	20	0.42	10	0.86								
Conventional	66	0.06	600	0.12								
Minimal-till	72	0.04	1030	0.05								
No-till	85	0.03	1760	0.02								
No. dates; months/year	4; Jun.–Oct./94		4; Jun.–Oct./94									

the LR treatment during all periods in 1992 to 1994; NT soil loss was 1400 times lower than that for LR during first-year-fallow in 1989 (Table 5). The MT treatment also offered considerable protective effect, with estimated soil losses 2500 times lower than LR in first-year fallow in 1992 to 1993 and 19 times lower than LR in first-year fallow in 1989. However, low crop plant growth in 1988 (930 vs. 3640 kg/ha 1986–1994 residue yield average: Table 1) led to an insufficient amount of residue remaining in 1990 after progressive losses due to fallowing tillage, over-winter decay, and disturbance by seed drilling (Table 4). Thus, the 0.03 vs. 40 Mg/ha estimated soil loss difference of NT vs. LR in the first-year-fallow period of 1989 was lessened to a 2 vs. 18 Mg/ha difference during the January to May second-year-fallow period in 1990. Disturbance by seeding re-

Table 5. Wind erosion hazard values of tillage treatments as soil losses calculated by application of the Revised Wind Erosion Equation (RWEQ) model to wind erodibility factors derived from measurements: soil loss ratios (SLR) for flat and standing residue; *K*, SLR for soil roughness effect; erodible fraction (EF) as a SLR.

Management period; no. days	Treatment†	WF‡	EF	SCF§	*K*	COG¶			Estimated Soil Loss (Mg/ha)
						SLR_F	SLR_S	SLR_C#	
									Mgha
				Dry Years					
1st year fallow	LORS	9.0, 28.7, and 59.1	0.443	3/16	0.587	0.67	0.51	1	40.4
05/06/89–	CONV		0.521	3/16	0.629	0.20	0.17	1	4.20
12/31/89;	MINL		0.537	1/16	0.701	0.14	0.15	1	2.11
245 days	NOTL		0.532	0/6	0.807	0.07	0.03	1	0.0287
2nd year fallow	LORS	10.0, 33.4, and 61.1	0.557	0/9	0.664	0.70	0.53	1	17.8
01/01/90–	CONV		0.562	0/9	0.776	0.08	0.39	1	1.21
05/05/90;	MINL		0.575	0/9	0.801	0.30	0.31	1	5.10
125 days	NOTL		0.574	0/9	0.867	0.17	0.26	1	2.30
After seeding	LORS	15,4, 33.1, and 59.1	0.471	1/7	0.289	0.84	0.79	1.00, 0.907,	12.5
05/06/90–	CONV		0.510	1/7	0.335	0.94	0.79	0.269, 0.32,	17.6
08/15/90;	MINL		0.572	1/7	0.366	0.84	0.35	and 0.01, 3 times	8.47
102 days	NOTL		0.580	1/7	0.478	0.60	0.35		8.00
				Wet Years					
1st year fallow	LORS	9.0, 28.7, and 59.1	0.295	3/16	0.226	0.40	0.15	1	1.20
05/06/92, 93–	CONV		0.258	2/16	0.115	0.08	0.03	1	0.00199
12/31/92; 93;	MINL		0.268	1/16	0.125	0.05	0.02	1	0.000487
245 days	NOTL		0.245	0/16	0.401	0.02	0.01	1	0.000040
2nd year fallow	LORS	10.0, 33.4, and 61.1	0.211	0/9	0.347	0.25	0.32	1	0.369
01/01/93, 94–	CONV		0.172	0/9	0.163	0.05	0.14	1	0.00137
05/05/93, 94;	MINL		0.201	0/9	0.204	0.04	0.09	1	0.000842
125 days	NOTL		0.215	0/9	0.524	0.02	0.05	1	0.000528
After seeding	LORS	15,4, 33.1, and 59.1	0.319	1/7	0.130	0.60	0.36	1.00, 0.907	1.11
05/06/93, 94–	CONV		0.278	1/7	0.119	0.20	0.27	0.269, 0.032,	0.136
08/15/93, 94;	MINL		0.321	1/7	0.136	0.20	0.22	and 0.01, 3 times	0.151
102 days	NOTL		0.292	1/7	0.168	0.04	0.11		0.00476

† Treatment designations: LORS, low-residue; CONV, conventional-till; MINL, minimal-till; NOTL, no-till.
‡ The minimum, median, and maximum values of the weather factor (WF) are given on the basis of a 15-day calculation period.
§ The 1st figure indicates the number of 5- to 16-day calculation periods out of the total number during the management period (the 2nd number) for which the soil crust factor (SCF) was not operational and had a value of 1.0; otherwise the value of (SCF) was 0.1749.
¶ Combined residue-plant materials factor.
# Values of SLR_C for successive calculation periods are given during the after seeding management period.

sulted in effective equality in estimated soil losses in the after-seeding period, 12.5 vs. 8.0 Mg/ha for LR vs. NT. Multi-year drought interacted with the long fallow period of the rotation (21-mo total) to remove protective effects of no-till management.

Thus, in a drought period, the wind-erosion hazard is accelerated (i) because the lack of precipitation leads to lowered residue production and subsequent increased residue-based wind erodibility, and (ii) because SIWE itself is increased. While the influences of environment and management on disappearance and decay of crop plant residues is relatively well understood (Steiner et al., 1994; Schomberg and Steiner, 1997), the relationships of environment to the dynamics of SIWE is currently under-researched and poorly understood (Merrill et al., 1999).

Our study was conducted on a productive, ordinarily nonerodible soil. On less productive, more fragile soils, crop plant growth will be lowered even more under chaotically occurring drought periods, and the protective effects of NT and MT practices will be significantly diminished. A fundamental contradiction exists in the use of crop–fallow rotations in dryland agriculture: the practice is widely believed to produce its greatest economic advantage during drought, when it becomes most dangerous to conservation of surface soil, which is the natural resource of highest societal value.

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